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MAGNETOSPHERIC STRUCTURE AND DYNAMICS:
A MULTISATELLITE APPROACH

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13. ABSTRACT (*Maximum 200 words*)

This report reviews progress during the first year of a contract to study magnetospheric structure and dynamics. Four areas of scientific investigation are highlighted. Pressure gradients form in the geotail because ions drift preferentially toward the dusk flank. These pressure gradients drive field aligned currents that close in the ionosphere and which provide a natural explanation of the Harang discontinuity when the full electrodynamics are modelled. Observations made during a passage by DE 2 through the dayside cusp at a time when the IMF was directed northwards are consistent with magnetic merging occurring on field lines that map to the poleward cusp boundary. We infer that tail lobe field lines were merging with magnetosheath field lines at the magnetopause tailward of the external cusp. During the March 1989 magnetic storm, the DMSP F9 spacecraft observed extensive substantial decreases in equatorial ion density in the post-dusk sector. Modelling calculations show that the depletions were cuased by unusually large upward flows moving the equatorial F region peak above 850 km. Calculations of ion cyclotron wave group velocities show that they are sensitive to both the hot and cold plasma populations. Calculated group delays agree with our earlier observations.

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I. Introduction

This contract funds a comprehensive five year study of magnetospheric structure and dynamics. There are four major areas of study: waves and wave particle interactions, magnetospheric tail and substorm dynamics, ionosphere-magnetosphere coupling, and active experiments. The first three areas are all central to our understanding of the geoplasma environment. Each plays a critical part in determining the pattern of plasma flows and currents and the distribution and properties of the plasma and energetic particles within the magnetosphere-ionosphere system. The last topic, active experiments, is an exciting emerging field in space plasmas that holds much potential. The major effort is directed towards the analysis of existing and newly acquired spacecraft data, with particular emphasis on multisatellite studies. The data analysis is complemented by theoretical and simulation studies, the development and maintenance of data analysis and display software for use in the data analysis, and the design of new innovative plasma and field instruments for use in the next generation of spacecraft. The overall goal of the study is to provide the understanding of the magnetosphere-ionosphere system needed to construct reliable models that will forecast the future state of the system.

This report focuses on four areas of scientific investigation in which significant progress has been made in the first year of the contract: the electrodynamics of the Harang discontinuity and geotail convection; signatures of magnetic merging observed on the poleward boundary of the cusp; understanding the causes of the extreme equatorial density depletions observed by DMSP F9 during the March 1989 magnetic storm; and modelling electromagnetic ion cyclotron wave group delays. Each of these topics is made the subject of one section of this report and has or will result in the publication of a scientific paper. Here we summarize the main scientific results and refer the reader to one or more of the publications arising out of our research for fuller details. A complete list of publications arising out of this research is contained in the last section of this report.

As this contract has been in effect for only one year, and most of the researchers working on this project have been supported by this contract for less than a year, all of the work described here was begun under other contracts, at Boston University and elsewhere, but substantial work was done and the work was completed under this contract.

II. The Physics of the Harang Discontinuity

We have developed a natural explanation of the Harang discontinuity that arises from the asymmetry of ion drift paths in the tail. The Harang discontinuity is the locus of points in the nightside auroral zone across which the meridional component of the ionospheric electric field reverses from a basically poleward field on the equatorward side to a basically equatorward field on the poleward side. In other words the Harang discontinuity represents a convergence of ionospheric electric field. The overall structure of this feature is evident in high-latitude radar observations, and in satellite measurements of both electric fields and ionospheric plasma flows.

Ions in the plasma sheet drift westward or duskward across the tail due to the magnetic gradient and curvature drifts. The westward curvature and gradient drift depletes dawnside flux tubes of energetic ions because there is no strong source of energetic plasma in the dawnside magnetopause boundary layer to replace those that have drifted westward. This dawnside depletion effect means that, on average, the duskside of the plasmasheet will have higher ion temperatures, pressures and flux tube contents, and hence stronger westward cross-tail drift current, than the dawnside. The deficit of dawnside current (or surplus of duskside current) must be compensated by upward currents from the ionosphere distributed across the tail to ensure current continuity. In the ionosphere, closure of this current requires a convergence of ionospheric Pedersen currents, and hence a convergence of electric field, directed towards the center of the upward current. This is exactly the form of the Harang discontinuity.

The requirement that Ohm's law be satisfied in the ionosphere creates an ionospheric electric field that maps back to the tail and modifies the plasma flow there. The region poleward of the Harang discontinuity maps well out into the plasma sheet. The equatorward electric field in this region of the ionosphere maps into an earthward electric field in the plasmasheet that drives a dawnward $\mathbf{E} \times \mathbf{B}$ flow that opposes the duskward gradient and curvature drifts. This helps keep the flow of ions in the plasmasheet directed towards the earth and reduces the loss of ions from the tail at the dusk flank. The poleward electric field observed equatorward of the Harang discontinuity maps to a tailward electric field at the inner edge of the plasma sheet. This drives a westward $\mathbf{E} \times \mathbf{B}$ flow that reinforces the westward curvature and gradient drift of ions around the dusk side of the earth towards the dayside magnetopause.

This argument was studied quantitatively by including these effects in the Rice Convection Model (RCM). This was done by extending the solution space much further down the tail and including a realistic plasma source boundary condition on the dawn flank of the tail. This resulted in a significant dawn depletion effect which caused a large band of upward Birkeland current to a drawn out of the central auroral zone on the nightside. The resulting latitudinal distribution of Birkeland currents matches those observed much better than those calculated in earlier runs of the RCM. The ionospheric convection electric field was modified to produce a strong convergence of electric field similar to that observed in the

Harang discontinuity. The dawn side depletion effect also results in a reduction of plasma sheet pressure in the near-Earth midnight sector of the plasma sheet due to the loss of ions through the dusk flank of the tail. However the flows driven in the tail by the electric fields associated with the Harang discontinuity tend to reduce these losses, which means that pressure can still build up to unstable levels in the inner plasma sheet even during magnetically calm intervals of slow convection. This latter effect will be explored in future work.

Principal Reference

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III. Cusp Electyrodynamics with Northward IMF

The DE-2 satellite often passes through the region of the ionospheric cusp/cleft that are are characterized by intense, highly-variable quasi-DC electric fields colocated with magnetosheath-like particles. In addition, during intervals of strong southward directed IMF, large spike-like electric fields are occasionally seen near the equatorward boundary of the cusp. These are thought to be the ionospheric signatures of magnetic merging at the dayside magnetopause. This hypothesis was tested and confirmed in an earlier case study during the large magnetic storm of September 6 1982, when DE-1 and DE-2 were conjugate and DE-1 crossed the magnetopause. A poleward-directed electric field spike was detected at the equatorward boundary of the cusp. This was interpreted as the ionospheric signature of the initial motion of the newly-merged flux tube in the direction of the local magnetosheath flow. However magnetic tension forces soon become dominant in determining flux tube motion, reversing the sense of flow. The electric field spike corresponds to a narrow region of plasma convection at the boundary of cusp precipitation in the direction of magnetosheath flow and is an indication that the satellite crossed the low-altitude footprint of the merging line. Another feature associated with magnetopause merging is a characteristic energy dispersion observed in the energetic ion fluxes near the equatorward boundary of the cusp. The highest energy ions are observed closest to the equatorward boundary of the cusp, and successively lower energies with increasing latitude.

If the electric field spikes seen at the equatorward boundary of the cusp during times of southward IMF are indeed low-altitude signatures of merging, then one might expect to observe similar electric field signatures near the poleward cusp boundary during periods of northward directed IMF if merging then takes place between the IMF and oppositely directed magnetospheric field lines at the magnetopause tailward of the cusp. We have studied in detail a single DE-2 cusp crossing that took place around 1900 UT on 17 February 1982 during a period of northward IMF. In the polar cap poleward of the cusp, plasma was flowing sunward towards the cusp. At the poleward boundary of the cusp precipitation, we observed an equatorward directed electic field spike, indicating a narrow region of duskward flow, followed by a much broader region of more moderate dawnward flow. The electric field spike was accompanied by an ion dispersion event, but in the opposite sense to that usually observed during southward IMF. That is the highest energy ions were observed at the poleward cusp boundary, and successively lower energy ions with increasing distance from the boundary. These observations are consistent with merging occuring on the high latitude magnetopause tailward of the cusp between IMF and tail lobe field lines. The global convection pattern has plasma flowing out of the polar cap, or in the tail lobe towards the magnetopause, where field lines reconnect with the IMF. Immediately after reconnection, magnetosheath flow drags the newly reconnected flux tubes rapidly duskward, but magnetic tension rapidly comes into play, reversing the flow so that the tubes convect tailward past the dawn flank. This gives rise to the electric field spike and subsequent oppositely directed electric field as well as the associated magnetic signatures of field aligned currents.

In addition to these larger scale features, a train of about three quasi-sinusoidal, electric

and magnetic field oscillations was observed just equatorward, or downstream, of the electric field spike. The oscillations had a period of about 2 s in the spacecraft frame, and there was an approximately 40° phase shift between the electric and magnetic variations. We put forward two alternative explanations for these waves which appear to be the result of the partial reflection off the ionosphere of hydromagnetic waves incident from above the spacecraft. One possibility is that what DE 2 observes is primary temporal in nature, that the waves have a period of 2 s in the plasma frame. This is near the ion cyclotron frequency, so the waves might well have been generated by the ions observed in the ion dispersion event being unstable to electromagnetic ion cyclotron wave growth. In this scenario the waves are generated higher up the field line and propagate down the field line to the ionosphere. Here they are partially reflected, so that DE 2 observes the interfering upgoing and downgoing waves, which explains the phase shift The three cycles observed represent the spatial extent of the source region, which is about 50 km at the DE 2 altitude of 850 km.

The second scenario links the oscillations more directly to the electric field spike at the polar boundary of the cusp. If this is an electric field experienced by each field line as it reconnects at the magnetopause and is dragged duskward by the flow in the magnetosheath, this electric field signature propagates down the field line as a shear mode Alfven wave. As the Alfven wave travels down the field line, the field line is convecting equatorwards at 100 or 200 m/s. On reaching the ionosphere, a few hundred kilometers below DE 2, the Alfven wave partially reflects and travels back up the field line which has in the meantime moved equatorward. The electric fields of the incident and reflected waves will tend to cancel, while their magnetic fields will tend to add, thus substantially changing the ratio of the electric and magnetic perturbations of the initial spike and the subsequent oscillations. The magnetopause, where field lines bend sharply and the Alfven speed changes abruptly, will also act as a partial Alfven wave reflector, so the wave will tend to bounce a few times between the ionosphere and magnetosphere before its energy is dissipated. This explains the train of three oscillations. The oscillation period is about 2 s in the spacecraft data, similar to the time scale associated with the spike. In 2 s the spacecraft moves about 14 km. The plasma, moving at 100-200 m/s along the spacecraft path, takes on the order of 100 s to move this distance. At typical magnetospheric Alfven speeds (1000-2000 km/s), a wave would travel 10-20 R_E in this time, not unreasonable for a trip from the magnetopause to the ionosphere and back again. Flux tube area increases by about a factor of 1000 between DE 2 altitude and the magnetopause where the field strength might be a factor of 1000 lower, so the 14 km distance along the spacecraft path increases to 500 km normal to the magnetopause at the magnetopause, or even more if flux tube shape is not preserved, which is probable. This is not an unreasonable thickness for a reconnection region.

At this stage we are not able to distinguish between these alternative scenarios on the basis of the data we've analysed. Hopefully analysis of further spacecraft passes through the cusp will allow us to decide which description is better able to explain the observations.

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IV. Equatorial Plasma Density Depletions during a Magnetic Storm

Early on 14 March, 1989, during a major magnetic storm, the thermal plasma probe on the DMSP F9 spacecraft detected extensive and dramatic decreases in the ion density at 840 km, near 2130 LT, during two consecutive transequatorial passes over South America. The order of magnitude decreases in ion density extended more than 4000 km along the satellite track. The depletions were accompanied by upward and westward plasma drifts, both in excess of 100 m/s. Their onsets and terminations were marked by extremely sharp density gradients. The satellite observed no similar depletions over the Atlantic during the preceding orbits. A partial depletion was detected over the eastern Pacific during the following orbit. The satellite ground track passed slightly west of a Brazilian TEC station and two Brazilian ionosondes during the orbit on which the first depletion was observed. The TEC fell far below normal during the night of 13-14 March. The ionosonde measurements indicate that, in the hour aftter sunset, before DMSP passed through the depletions, the F2 layer rose rapidly and disappeared, but at the time of the first DMSP pass through the depletion, hmF2 was decreasing over one of the stations.

A sister spacecraft, DMSP F8, orbits in the dawn-dusk meridian. When this spacecraft passed over South America at dusk on 13 March, some three hours before DMSP F9 detected the depletions, it detected extemely large ion densities and upward and westward drifts. Twelve hours later, during two dawn passes over the eastern Pacific, DMSP F8 did detect depletions somewhat similar to those seen by DMSP F9, accompanied by a large westward drift. These morning side depletions could well be the remnants of those detected earlier, in the premidnight sector, by DMSP F9.

Large eastward electric fields will drive large upward drifts at low latitudes. As the DMSP orbit is normally well above the altitude of the F2 peak density, upward drifts normally give rise to increased not decreased densities. However, we argue that on this night the electric fields and hence the drifts were so strong that the F2 peak was lifted above the DMSP altitude, placing the spacecraft in the very low density plasma below the nighttime F2 peak. When an equatorial flux tube is raised, plasma tends to fall down the flux tube under the force of gravity, raising plasma densities at lower altitudes off the equator. Model calculations of the effect of large sustained upward drift at the equator combined with gravity driven field aligned flows reproduce the sorts of depletion that were seen by DMSP F9. The sharp boundaries to the depletion are created naturally by a convergence of the plasma drift paths.

The cause of the intense upward drifts that produced the plasma depletions can not be unambiguously determined. However there are two processes that can give rise to an eastward electric field at the equator during a large magnetic storm. During large magnetic storms the normal upper atmosphere circulation patterns are disturbed by the additional thermal inputs. The new circulation drives an atmospheric dynamo that can reverse the electric field that is normally westward in this local time sector, which results in upward drifts. Under normal conditions, magnetospheric electric fields are shielded from mid and low

latitudes by the action of the ionosphere itself. However during large disturbances, especially if the region of sunward convection comes close to the earth, this shielding can break down. If this occured, the magnetospheric convection electric field could have penetrated to the equator. It is likely that a combination of these two effects produced the large upward drifts observed by both DMSP spacecraft, and hence caused the observed depletions. That the depletions were observed shortly after the ring current reached its maximum intensity and nearly a day after the first ssc of the storm means that the storm dynamics were undoubtedly important in their formation. The hole's location between the evening terminator and the South Atlantic Anomaly (where intense particle precipitation raises ionization levels) implies a role for conductivity gradients in enhancing the electric fields.

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V. Ion Cyclotron Group Delay near the Plasmapause

Electromagnetic ion cyclotron waves are generated near the magnetic equator through an instability driven by energetic ion temperature anisotropy. The waves propagate along magnetic flux tubes, and many are observed on the ground as pc1 magnetic pulsations. These often exhibit a distinctive wave packet structure believed to be the result of wave packets bouncing back and forth along a flux tube producing the repetitive structure that gives rise to the name pearl pulsations. In an earlier report we compared ion cyclotron waves observed by the DE 1 spacecraft near the equatorial plane near L=4 with ground based observations of pc1 pulsations observed near the foot of the DE 1 field line by the AFGL Magnetometer Network. For three of the six events observed simultaneously in space and on the ground, we were able to estimate the delay time for the signal to propagate from the equator to the ground. The estimates for the different events ranged between 35 and 100 s.

In this work we compare these measurements with calculations of the group delay made using the full hot plasma dispersion relation integrated along a dipole field line from the equator to the ground. The plasma parameters used in the calculations are based on the plasma and particle measurements made by DE 1 at the time of the wave events. As the parameters are not always measured precisely, we conducted a variation analysis to determine how sensitive the group delay is to the various plasma parameters, and also compared our results to the results obtained earlier using only the cold plasma dispersion relation.

We found that the density of both the hot and cold species affect the wave group velocity significantly, especially near the equatorial plane where the group velocity is smallest, and so where it has the largest effect on the total group delay. Including the full dispersion relation as opposed to the cold plasma dispersion relation produced changes in the group delay on the order of 10%. Using measurements from the Energetic Ion Composition Spectrometer, the Plasma Wave Instrument and the Retarding Ion Mass Spectrometer to define the hot and cold plasma environments, we obtained good agreement between our calculated group delays and those we obtained earlier from a cross correlation of the waves measured by DE 1 and on the ground.

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VI. Publications

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